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VLBI Intensive Sessions Revisited

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Abstract

Several aspects of VLBI Intensive sessions are revisited in this paper. On the one hand, an extension of the observing time from one to two hours is considered. For this purpose, in late 2011 and early 2012, some special Intensives were observed. On the other hand, changes of the parameterization of the zenith wet delay, as well as a modified weighting, were applied in our analysis. The approach of extending the Intensives to two hours leads to an increased precision of UT1 as expected. Furthermore, a parameterization of time variable parameters seems useful and especially the least squares collocation approach is a promising method to realize this. Finally, a re-weighting via Variance Component Estimation provides more stable results for Intensives with more than one baseline.

1. Introduction

VLBI Intensive sessions (INTs, [6]) are performed to provide daily UT1 measurements between the irregularly occurring 24-h sessions. Currently, INTs have a duration of one hour and are observed on small networks. Three types of INTs exist. INT1s are measured on the baseline Kōke'e Park (KK, Hawaii, USA) – Wettzell (WZ, Germany), INT2s on the baseline Tsukuba (TS, Japan) – WZ, and, INT3s on a three-station network with Ny-Ålesund (NY, Spitsbergen, Norway), TS, and WZ. As the INTs are made up of one or three baselines, there are weak observing configurations which lead to systematically different UT1 estimates. These are shown, strongly smoothed by splines, in Figure 1. Obviously, the results of INT2s and INT3s seem to agree better with each other in comparison to INT1s. This indicates a clear network effect on the UT1 values derived from Intensive sessions, as INT2s and INT3s are dominated by the TS – WZ baseline. In addition, a negative impact was shown, e.g., by [7], when Intensives were used in an inter-technique combination as the agreement of UT1 to excitations by geophysical fluids degraded. This leads to some reservations against the current concept of Intensive sessions.

The problems mentioned above might not only be caused by network effects. Other possible reasons can be seen in the scheduling and even in the observing interval of one hour which might

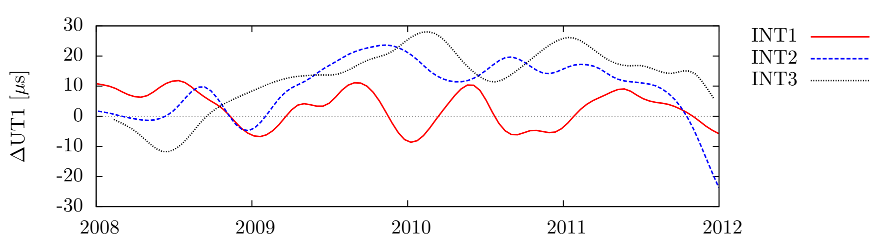

Figure 1. Strongly smoothed UT1 estimates w.r.t. IERS-08C04 for the three types of Intensive sessions: INT1 (solid red line), INT2 (dashed blue line) and INT3 (dotted black line).

be too short for reliable UT1 estimates. Finally, an INT1 is performed in the evening around 18:00 UTC while INT2s and INT3s are measured in the morning around 7:00 UTC. Thus, they measure sub-daily UT1 effects at different phases, which is a problem when the models for sub-daily variations of the Earth orientation parameter are not sufficiently accurate.

To overcome some of the deficiencies and to improve the Intensives, several investigations have been carried out so far. Special R&D sessions with 1-h KK − WZ databases and 24-h databases for the remaining network (R&D 907 − 910 and 1001 − 1005) took place to validate and to improve the scheduling [1]. These contain approximately 200 INTs. Furthermore, an extension to 2 hours of observation (three INT3s in late 2011, and three INT2s in early 2012) has recently been performed.

In this paper the 2-h approach is validated. For this purpose, the original 2-h INTs were used and some more 2-h INT3-like sessions were simulated. Furthermore, the subsequent 1-h R&D-INTs were consolidated to 2-h durations. In addition, some special analysis options were applied within the present analysis to revise the analysis procedure as well.

The solutions were done with Calc/Solve ([2], [4]). However, Solve was changed in a way that the completely unconstrained equation system can be exported. This equation system was then processed with a back-end, where all modifications are implemented.

2. Analysis Options

The analysis setup for Intensive sessions is and has to be different from 24-h sessions due to the limited number of observations. In the analysis presented here, some modifications are made in comparison to the standard setup of an INT analysis. Three solution approaches deal with the troposphere handling, and another approach deals with a modified re-weighting of the observations.

Usually, a constant zenith wet delay (ZWD) is estimated for each telescope, and a relative linear clock behavior is estimated besides the target parameter UT1. Here, three different troposphere modeling options are compared. First, a constant ZWD and, secondly, continuous piecewise linear function (CPWLF) ZWDs were estimated in a classical least squares (LSQ) adjustment (e.g., [3])

$$\mathbf{\Delta\tilde{x}} = (\mathbf{X}^T\mathbf{\Sigma}_{yy}^{-1}\mathbf{X})^{-1}\mathbf{X}^T\mathbf{\Sigma}_{yy}^{-1}\mathbf{\Delta y}, \tag{1}$$

where $\mathbf{X}$ denotes the Jacobian matrix with the partial derivatives of the observation equations w.r.t. the estimated parameters $\mathbf{\Delta\tilde{x}}$. The vector $\mathbf{\Delta y}$ contains the reduced observations and the matrix $\mathbf{\Sigma}_{yy}$ represents the variance-covariance matrix (VCM) of the observations. As a third option, ZWDs were handled as stochastic parameters by using the LSQ collocation method [5] instead of the CPWLF representation in the classical LSQ adjustment.

The LSQ collocation had already been applied in VLBI analysis (e.g., [8]). However, here we use it as a replacement for the classical LSQ adjustment, while the processing chain, the applied models, and the set of observations remain the same. With the LSQ collocation, the deterministic parameters can be estimated [8]

$$\mathbf{\Delta\tilde{x}} = (\mathbf{X}^T(\mathbf{B\Sigma}_{zz}\mathbf{B}^T + \mathbf{\Sigma}_{yy})^{-1}\mathbf{X})^{-1}\mathbf{X}^T(\mathbf{B\Sigma}_{zz}\mathbf{B}^T + \mathbf{\Sigma}_{yy})^{-1}\mathbf{\Delta y}, \tag{2}$$

where the matrix $\mathbf{B}$ consists of the partial derivatives of the delay w.r.t. the stochastic parameters $\mathbf{z}$, and the matrix $\mathbf{\Sigma}_{zz}$ describes the stochastic properties of these parameters. Besides the estimated deterministic parameters $\mathbf{\Delta\tilde{x}}$, the stochastic signals can be determined as well

$$\mathbf{\Delta\tilde{z}} = \mathbf{\Sigma}_{zz}\mathbf{B}^T(\mathbf{B\Sigma}_{zz}\mathbf{B}^T + \mathbf{\Sigma}_{yy})^{-1}(\mathbf{\Delta y} - \mathbf{X\Delta\tilde{x}}). \tag{3}$$

The VCM of the stochastic parameters, i.e. ZWDs, was determined from the LSQ estimates of Continuous VLBI Campaigns in 2002, 2005, and 2008. From the equidistant ZWD time series with a temporal resolution of 20 minutes, an empirical auto-covariance function was determined. In a second step, a semidefinite function [8]

$$C(t) = \frac{C(0)}{\cos\phi} exp(-\alpha t)\cos(\beta t + \phi) \tag{4}$$

was fitted to the empirical function by estimating the parameters α, β, and ϕ. The VCM of the stochastic parameters was then built by the variance $C(0) = 2\ \text{cm}^2$ and the covariances for time difference t: $C(t)$.

As a last analysis option, a modified re-weighting via variance component estimation (VCE, e.g., [3]) was applied to the classical LSQ adjustment. In a first step the parameters are estimated and the post-fit residuals are determined

$$\mathbf{r} = \mathbf{\Delta y} - \mathbf{X}\mathbf{\Delta}\tilde{\mathbf{x}}. \tag{5}$$

To derive baseline-dependent variance components, the squared sum of the residuals is calculated for each baseline and scaled by the partial redundancy of this particular baseline f_i

$$\tilde{\sigma}^2_{0i,v} = \frac{\mathbf{r}^T \mathbf{\Sigma}_{yy}^{-1}\mathbf{r}}{f_i}, \tag{6}$$

where the partial redundancy is derived from the VCM of the residuals which belong to one baseline

$$\mathbf{\Sigma_{rr}} = \sum_{i=1}^{n} \mathbf{\Sigma_{rr,i}} = \mathbf{\Sigma_{yy}} - \mathbf{X}(\mathbf{X}^T\mathbf{\Sigma}_{yy}^{-1}\mathbf{X})^{-1}\mathbf{X}^T, \tag{7}$$

$$f_i = \sum_{i=1}^{m} \Sigma_{rr,i}(i,i) = tr(\mathbf{\Sigma_{rr,i}}), \tag{8}$$

where n is the number of baselines in the solution and m is the number of observations on a specific baseline. In a second step, the VCM of each group of observations is updated

$$\mathbf{\Sigma}_{yy,i,v} = \sigma^2_{0i,v}\mathbf{\Sigma}_{yy,i,v-1} \tag{9}$$

and the LSQ adjustment is performed again. This iteration ends if $\sigma^2_{0i,v}$ are numerically 1.

3. Results

3.1. LSQ Collocation and Re-weighting

To present the impact of modified analysis options, the 2-h long Intensives as well as the R&D-Intensives are used. In Figure 2, the results from the 2h INT3s in 2011 and INT2s in 2012 are shown for the different analysis approaches.

The modified re-weighting only has an impact on the results of the INT3s, as they consist of three baselines, while the INT2s are only single-baseline sessions. Thus, an INT3 contains three independent groups of observations and an INT2 only one. As expected, the re-weighting by VCE leads to significant changes of the estimates only for sessions where large differences between the

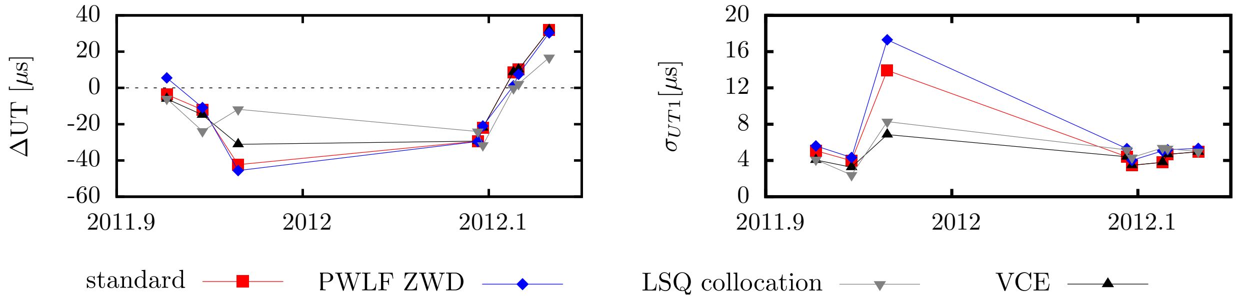

Figure 2. UT1 minus IERS-08C04 values (left) and their standard deviations (right) from the 2-h Intensives analyzed with different analysis options. INT3s took place in 2011 and INT2s in 2012.

post fit residuals of the baselines exist (e.g., 11DEC19XK: third data point in Figure 2). However, the re-weighting reduces the standard deviations for all three INT3s.

The ZWD handling always has a significant impact. The two classical LSQ solutions show a similar behavior, where the standard approach with one constant ZWD parameter (red line with squares in Figure 2) leads to marginally lower standard deviations of the UT1 estimates than the CPWLF approach (blue line with diamonds). Thus, the precision of the UT1 estimates is not improved by ZWDs with a temporal resolution of 20 minutes. But, the stochastic treatment of the ZWD in a LSQ collocation approach (grey line with lower triangles in Figure 2) results in a more precise UT1 estimation. Obviously, a more realistic representation of the troposphere leads to a more precise UT1 estimation. The UT1 estimates of this approach are different from the results of the classical LSQ adjustment. In further investigations, a comparison with geophysical excitations should show which results are more accurate.

A first hint of the correctness of the LSQ collocation results is gained from the analysis of the R&D sessions. For the R&D-sessions, the root mean square (RMS) and weighted RMS (WRMS) differences of the approximately 200 UT1 estimates from the R&D-INTs w.r.t. the results of the corresponding 24-h sessions were calculated. Between the standard approach and the use of CPWLF ZWDs, the UT1 repeatability is not significantly improved. A slight enhancement is gained by using stochastic ZWDs within the LSQ collocation method as shown in Table 1.

Table 1. RMS and WRMS differences between UT1 estimates from the R&D INTs and the corresponding 24-h sessions.

approach	WRMS [μs]	RMS [μs]
standard	19.2	23.9
CPWLF	18.6	23.3
LSQ-colloc.	18.6	22.0

3.2. 2-h vs. 1-h Intensives

To validate the test schedules of Intensives with a duration of 2-h in comparison to standard 1-h Intensives, several sessions were used. On the one hand, the dedicated 2-h long test INTs were either analyzed directly or split up into 1-h bins. In addition, subsequent 1-h KK – WZ R&D-INTs were stacked to 2-h sessions or analyzed directly as 1-h Intensives. Finally, simulations of 1-h and 2-h INTs for three months were created. The solutions were done in a LSQ adjustment with VCE re-weighting, and 30 minute CPWLF ZWDs were estimated. Thus, for each 2-h INT two 1-h INTs exist, and vice versa. The standard deviations of the UT1 estimates are shown in Figure 3.

As expected, the standard deviations of UT1 of 1-h Intensives are bigger by a factor of approximately $\sqrt{2}$ than those of 2-h INTs. Thus, the increased precision is mainly due to the doubled number of observations. The estimates of a 2-h Intensive (not shown here) are in general between the two 1-h Intensive results. However, they are not strictly in the middle between the first and the second hour. Furthermore, the RMS differences of UT1 from 2-h INTs vs. 1-h INTs (R&D-sessions) to the UT1 estimates of the 24-h sessions is about 15% lower.

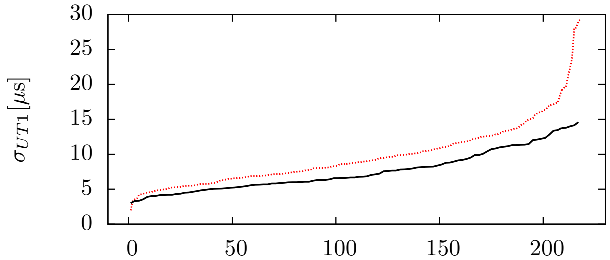

Figure 3. Sorted standard deviations of all Intensive sessions. The dotted red line indicates the 1 h sessions and the solid black line the 2 h sessions.

4. Conclusions

For some special Intensives, non-standard analysis options have been used. For 2-h INTs, a parameterization of time variable ZWD seems useful. In particular, the LSQ collocation approach is a promising method to realize this. Furthermore, a re-weighting via VCE has been implemented. In this way, the Intensives with more than one baseline provide much more stable results.

Concerning the duration of the Intensives, the 2-h approach is promising. As expected, the 1-h INTs are smoothed, and the standard deviations are lowered by a factor of approximately $\sqrt{2}$ due to having twice as many observations.

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